

**DEVELOPMENT OF A PYROLYSIS WASTE RECOVERY  
MODEL WITH DESIGNS, TEST PLANS, AND APPLICATIONS  
FOR SPACE-BASED HABITATS**

**Final Report**

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## ABSTRACT

Extensive literature searches revealed the numerous advantages of using pyrolysis as a means of recovering useable resources from inedible plant biomass, paper, plastics, other polymers, and human waste. A possible design of a pyrolysis reactor with test plans and applications for use on a space-based habitat are proposed. The proposed system will accommodate the wastes generated by a four-person crew while requiring solar energy as the only power source. Waste materials will be collected and stored during the 15-day lunar darkness periods. Resource recovery will occur during the daylight periods. Useable gases such as methane and hydrogen and a solid char will be produced while reducing the mass and volume of the waste to almost infinitely small levels. The system will be operated economically, safely, and in a non-polluting manner.

## INTRODUCTION

In a controlled ecological life support system (CELSS) such as a space-based (lunar/Mars) habitat, water, food, and oxygen must be stored and recycled. The problems of mass and volume limitations and infrequent resupply dictate that artificial methods be employed to supply the needs of the inhabitants (15). One of the most important aspects of a CELSS involves a closed loop system (14). A CELSS must have the ability to: a) process human waste and plant biomass and recover resources from these materials; b) recondition and revitalize the air by using waste materials; c) maintain a mass balance within the system; d) provide safe and reliable life support for long-duration missions; e) attain a high level of self-sufficiency; f) lower the expense and simplify the problems related to resupply; and g) provide an Earth-like environment that is conducive to productivity (6,11).

### Requirements of a CELSS

The waste resource recovery portion of a CELSS will consist of a waste and water management subsystem, an atmosphere management subsystem, and a food management subsystem (5). The outputs of one subsystem should match the requirements of the others while observing quality and quantity tolerances (6). The design of such a CELSS should also permit future expansion, and should be safe, reliable, flexible, and easily maintained. A CELSS that incorporates biological and physicochemical (B/PC) technologies to recycle water, air, food, and biomass holds the ultimate promise of allowing humans to become successfully established outside the Earth's biosphere (10).

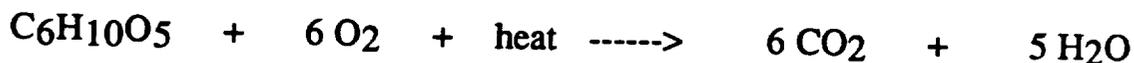
Spaceflights through the Space Shuttle era have not been dependent on recycling and regeneration of useful resources because of the short duration of the flights. Instead, waste materials have been stabilized, stored, and returned to Earth for analysis and disposal. This will not be feasible on lunar and Mars missions. The majority of the food on future, long-duration flights and missions must be grown in a CELSS. Most of the plant biomass is inedible and must be processed to supply carbon dioxide, water, and nutrients for plant growth, or fuel for other systems. It is estimated that inedible plant biomass and paper products will constitute approximately half of the total dry, solid waste material generated in a CELSS (13).

The simplest, and probably the most obvious, method of recovering some of the value from any organic material is by burning it for its energy

content (4). The two processes used for the destruction of materials by heating are incineration and pyrolysis.

## **Incineration**

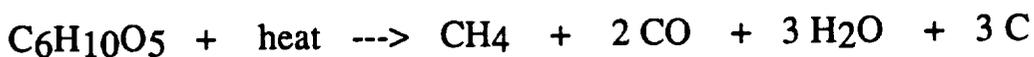
Incineration is the complete oxidation of waste using either pure oxygen or oxygen diluted with an inert gas. A temperature of 1000°C and a pressure of approximately one atmosphere are required. All types of combustible materials such as inedible plant biomass, paper, plastics, food waste, human waste, etc. may be treated. The incineration process usually involves two major steps: a) initial heating to sterilize and to vaporize the volatiles; and b) combustion of the dry waste. The process is relatively fast and results in 97 to 99% reduction of the waste. The end product is usually a fine, dry powder (7). Most incinerators contain two chambers. In the primary chamber auxiliary burners dry, volatilize, and ignite the waste. The amount of air present is in 75 to 100% excess. When combustion is sustained, the burners are turned off. The gases and combustibles flow into the secondary chamber for burn completion. The air is maintained at an excess level of 75 to 150%. The excess air, turbulence, and retention time provide conditions for complete combustion (12). The chemical reaction for the incineration of cellulosic materials is:



## **Pyrolysis**

Pyrolysis is the chemical destruction of a carbonaceous material by heating to 400 to 1000°C in the absence of oxygen, or in a controlled oxygen environment. The pyrolytic process results in the formation of four phases of products: a) a gaseous component including hydrogen, methane, carbon monoxide, and carbon dioxide; b) an oil including organic acids, alcohols, ketones, etc.; c) a char including carbon and inert compounds; and d) an aqueous phase containing some water-soluble compounds. In general, the faster the decomposition of the materials, the higher the yield of gas, whereas a long, slow heating process results in higher proportions of oil and char. Also, upon rapid heating in the absence of oxygen, cellulose molecules "explode," and the fragments are free to form simple compounds such as methane, carbon monoxide, hydrogen, and water (1). During the pyrolytic process, cellulose increases in porosity and swells as volatiles are evolved. Pyrolysis begins at approximately 200°C,

and tars evolve. As the temperature rises the products decompose or crack, forming hydrogen-rich gaseous compounds and solid carbon which approaches graphitic carbon. The pyrolysis of cellulose reaches completion between 600 and 800°C (2). The overall reaction for the pyrolysis of cellulose is:



The reaction appears to be endothermic at lower temperatures and exothermic at higher temperatures. Retention time is usually between 12 and 15 minutes (8). Some of the gases produced are combustible and have value by providing heat to the effluent gases. The carbon residue, a char, can also be used as a fuel. No oxygen is added, and the starting material is only cellulose. Since the original material is not necessarily pure cellulose, the effluent gases may contain some simple and complex organic compounds. The char may also contain some minerals, ash, and other inorganics as well (4).

The major concerns of a pyrolysis and/or incineration system in a space-based habitat are the use of high temperature, explosion potential, energy requirements, fire propagation, production of toxics, required maintenance, efficiency, mass and volume requirements, pre- and post-treatment of waste, requirement for a continuous system, and longevity of the system (13).

## DISCUSSION

Comparison of the advantages and disadvantages of pyrolysis versus incineration indicate that pyrolysis might possibly be the most appropriate physicochemical combustion technology for the recovery of resources from waste materials. The advantages of pyrolysis include the following: a) greater stability with little response to change in feed rate and therefore easier to control; b) 15 to 25% higher process rates (feed capacity per square foot of bed area); c) fewer and smaller particulates; d) less or no supplemental fuel required; e) generation of useable gases; and f) smaller mass and volume waste requirement (3). A pyrolysis reactor on the lunar surface will require no fuel other than that supplied by the sun through the use of solar concentrators. Also, a purge gas may not be needed since the vacuum of space could be used to evacuate the air from the chamber. In some instances a combined incineration/pyrolysis system might be employed.

The actual results of a commercial pyrolytic process are shown in Table 1. The effluent gases of three wastes indicate high percentages of two gases that are potential fuels (methane and hydrogen).

**TABLE 1.- PYROLYSIS TEST RESULTS\***

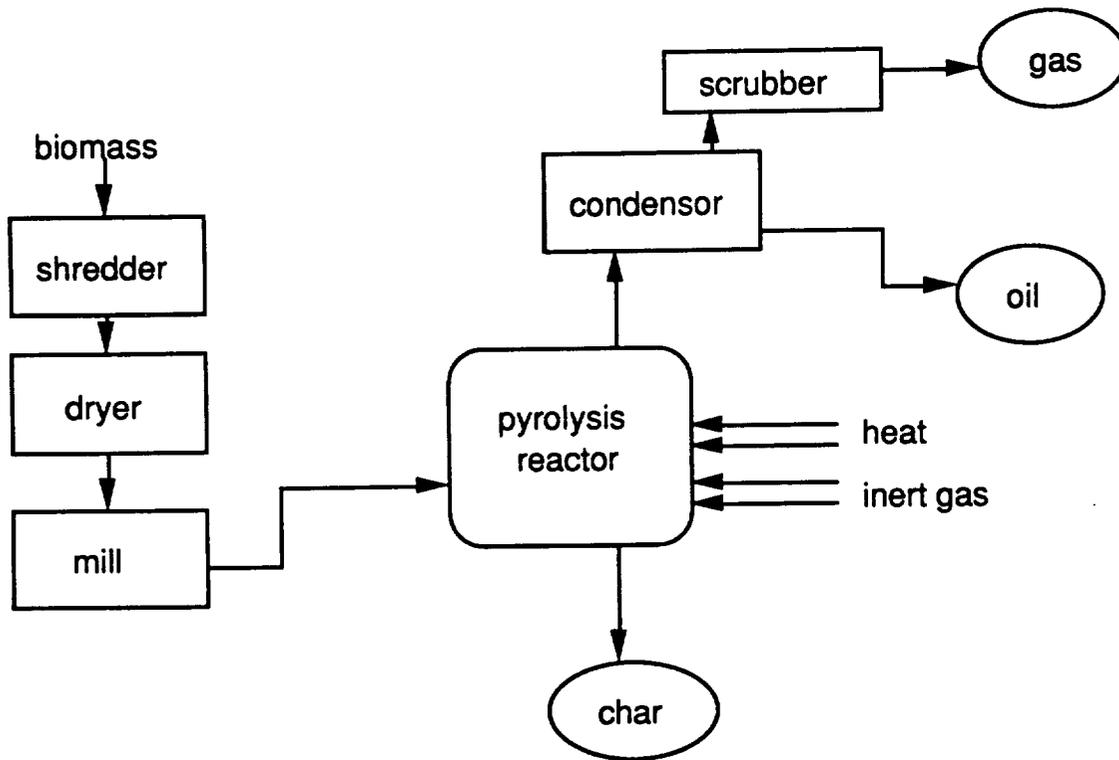
<i>Gases Produced (mol %)</i>	<i>Type of Waste</i>		
	<i>Liquid Organic</i>	<i>Garbage</i>	<i>Drugs</i>
Hydrogen	34.60	30.29	---
Carbon dioxide	6.22	14.19	---
Ethylene	8.52	8.06	10.37
Ethane	2.35	0.91	4.13
Acetylene	0.15	0.43	0.01
Oxygen	---	---	---
Nitrogen	0.70	0.48	---
Methane	25.53	10.80	78.78
Carbon monoxide	6.22	26.25	---
Propane "plus"	15.71	8.58	6.71
Hydrogen sulfide	---	---	---

\* Test results are from a pyrolysis system invented, owned, and operated by Benjamin P. Fowler, Fowler Engineering Company, Houston, Texas. Complete descriptions are given in U.S. Patent No. 4,934,286. The mention of a vendor does not imply endorsement by NASA.

### **Proposed System**

The proposed system will operate at high temperatures (up to 1000°C). The power source for the initial test model will be either an electrical furnace supplying heat to ceramic plates, a carbon arc, a graphite resistance furnace, or a gas burner. The actual space-based system will use solar concentrators, or electrical power from solar panels or a nuclear power source. The system will accommodate plant biomass, plastics, other polymers, human wastes, etc.

Figure 1 is a schematic of the proposed pyrolytic process.



**Figure 1.- Schematic of the Pyrolysis Process**

### **Proposed Test Plans**

The pyrolysis reactor shall be tested using several waste materials, individually and collectively. The test materials should include inedible plant biomass, paper, plastics, other polymers, and possibly human biomass waste. Test conditions shall be varied to attain the optimum rate and degree of pyrolysis with the recovery of all products for analysis. Useable products should be identified for each type of waste. The test conditions shall initially include the items shown in Table 2.

**TABLE 2.- PYROLYSIS TEST CONDITIONS**

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Maximum temperature	1000°C
Pressure	ambient
Amount of biomass	10 kg
Moisture content	< 3%

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### **Steps in the Pyrolysis Process**

The steps in the pyrolytic process are outlined in Table 3.

**TABLE 3.- PYROLYSIS PROCEDURES**

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1. Biomass is collected.
  2. Biomass is shredded.
  3. Biomass is dried to reduce moisture content to 3% or less.
  4. Biomass is milled to reduce particle size to 30 microns or less.
  5. Biomass is fed into the pyrolysis reactor vessel.
  6. Oxygen and air are expelled from the reactor by the introduction of an inert gas or by evacuation to the vacuum of space.
  7. The reactor vessel is sealed to prevent the introduction of additional oxygen or air.
  8. The vessel is heated to 1000°C where pyrolysis is carried to completion while gases are collected.
  9. Effluent gases are scrubbed, separated, and condensed if necessary.
  10. The system is shut down for maintenance if required.
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### **Design of the Pyrolysis Unit**

The pyrolysis unit will be constructed, tested, and monitored under experimental conditions. The prototype laboratory model should be built to the specifications of a lunar/Mars model and should be tested under the

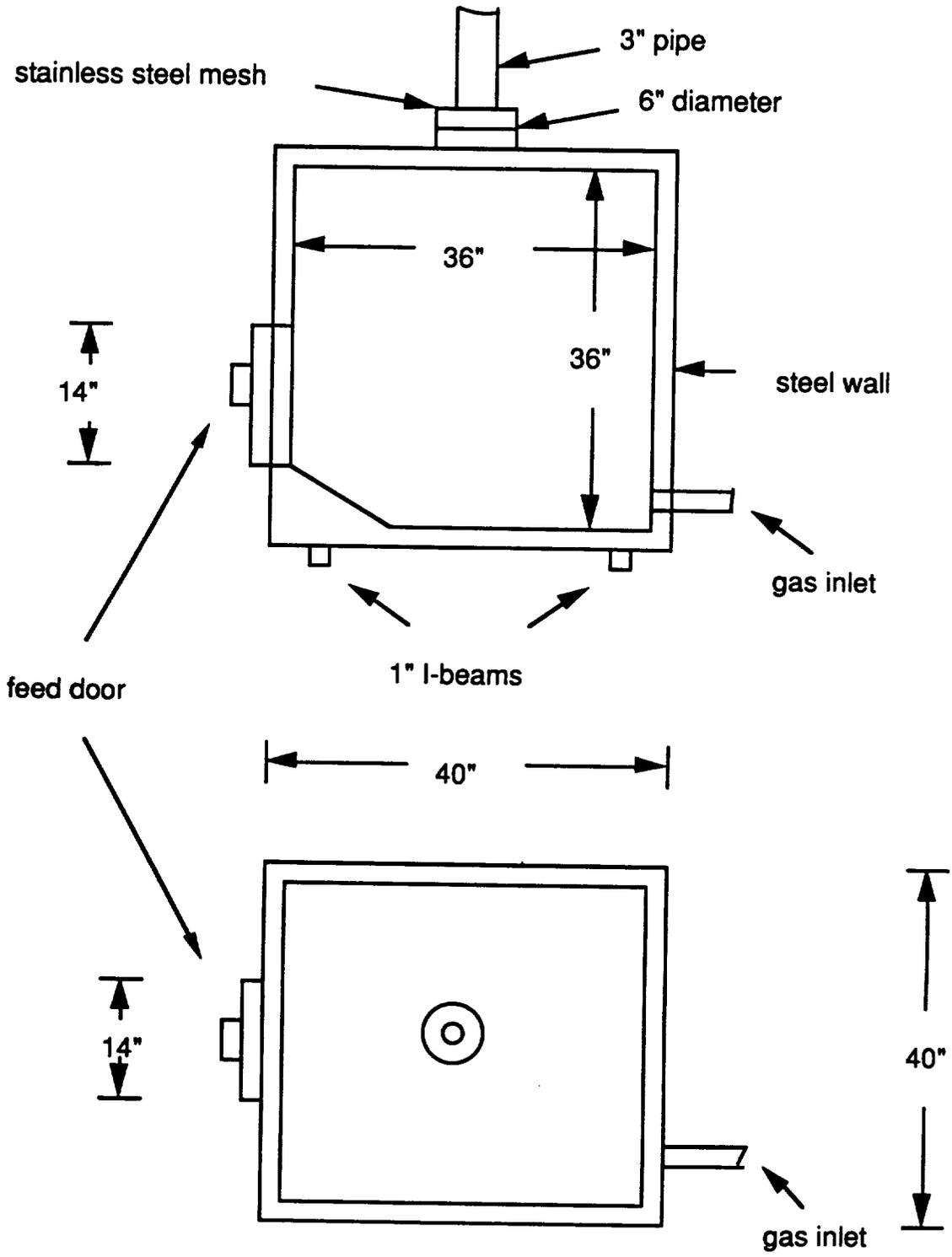
conditions that exist on the surfaces of those bodies. Careful monitoring of effluent gases should be conducted to assure that no toxic gases will be released to space or to the atmosphere of Mars. Analysis of the products of the pyrolysis of various substances should also be conducted to determine their uses as fuels, nutrients, etc. Numerous pyrolysis reactors in commercial use offer suggestions for a possible space-based model. Some of the criteria for a lunar/Mars pyrolysis reactor system are listed in Table 4.

#### **TABLE 4.- PYROLYSIS REACTOR SPECIFICATIONS**

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1. The reactor vessel shall be relatively compact.
  2. The reactor vessel and all hardware shall be constructed of corrosion proof materials.
  3. The system shall tolerate temperatures up to 1000°C.
  4. The system shall accommodate a minimum of 10 kg of waste per day.
  5. The system shall operate in a batch mode.
  6. The system shall permit the recovery of useful gases and solids.
  7. The system shall be easily maintained.
  8. The system shall be safe and reliable.
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Figure 2 shows a possible design configuration for a pyrolysis reactor.



**Figure 2.- Pyrolysis Model**

## CONCLUSIONS

Pyrolysis appears to be a highly efficient method for the recovery of useful resources from inedible plant biomass, paper, plastics, other polymers, and even human waste. Solar furnaces can supply the power for the operation of the unit while methane and hydrogen can be collected for use as fuels. The hydrogen could also be used to produce water (assuming that oxygen can be obtained from the minerals on the moon and Mars). The gases can be scrubbed to remove possible toxic materials. The char and oils resulting from the pyrolysis process can also be used as fuels. The system will be capable of batch mode operation and can possibly be integrated with other physicochemical and biological systems of a CELSS. The system should be relatively inexpensive, easily maintained, and should be extremely durable and safe. Further studies are essential including the actual construction and testing of the pyrolysis unit.

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